You have downloaded a document from
RE-BUŚ
repository of the University of Silesia in Katowice

Title: Water balance and chemical denudation in the unglaciated Fugleberget basin (SW Spitsbergen)

Author: Marian Pulina, Wiesława Krawczyk, J. Pereyna

Citation style: Pulina Marian, Krawczyk Wiesława, Pereyna J. (1984). Water balance and chemical denudation in the unglaciated Fugleberget basin (SW Spitsbergen). "Polish Polar Research" (1984, no. 3/4, s. 183-205).

Uznanie autorstwa - Użycie niekomercyjne - Bez utworów zależnych Polska - Licencja ta zezwala na rozpowszechnianie, przedstawianie i wykonywanie utworu jedynie w celach niekomercyjnych oraz pod warunkiem zachowania go w oryginalnej postaci (nie tworzenia utworów zależnych).

UNIWERSYTET ŚLĄSKI W KATOWICACH
Biblioteka Uniwersytetu Śląskiego
Ministerstwo Nauki i Szkolnictwa Wyższego

POLISH POLAR RESEARCH (POL. POLAR RES.) POLSKIE BADANIA POLARNE	5	3—4	183—205	1984

Marian PULINA [1]), Wiesława KRAWCZYK [1]), Jerzy Pereyma [2])

1) Institute of Geogrphy, Silesian University
2) Geographical Institute, Wrocław University

Water balance and chemical denudation in the unglaciated Fugleberget basin (SW Spitsbergen)

ABSTRACT: This paper gives the results of investigations carried out in the Fugleberget basin which lies on the northern shore of the Hornsund Fiord, in the unglaciated region of raised sea terraces and on the slopes of the Fugleberget (569 m a.s.l.) and the Ariekammen (511 m a.s.l.). The investigations were carried out between 23 July, 1979 and 4 September, 1980, including the polar night. The Fugleberget basin represents well the area of sea terraces and coastal mountains uncovered with glacier and occupying large areas in West Spitsbergen. These areas are characterized by the presence of permafrost.

The aim of investigations was to determine such fluvial processes as the duration of the hydrological period, the manner of water supply to the basin and an attempt to define the elements of the water balance. In addition studies were made on hydrological processes, particulary changes in the chemical composition of water, and the magnitude of denudation determined.

Key words: Arctic, Spitsbergen, water balance, chemical denudation

1. Introduction

Hydrological and hydrochemical investigations take a large part in the research programmes of Polish expeditions to Spitsbergen. They are carried out in several hydrological basins set around the Hornsund Fiord. The aim of these investigations is to determine the fluvial processes and chemical denudation in each of the different landscape areas in West Spitsbergen. These investigations cover unglaciated raised sea terraces, the slopes of coastal mountains and the glaciated valleys descending to the Hornsund Fiord. Such investigations were performed in 1970–1975 and 1978–1980 in the basin of the Werenskiold Glacier and in the partly glaciated Brattegg Valley

(Baranowski, Głowicki 1975, Pulina 1974). In 1978 and 1979 investigations were carried out in the basin of the Nordfall Glacier in Sørkappland (Leszkiewicz 1979, Wach 1980) and in 1979 and 1980 in the Fugleberget basin (Krawczyk, Pulina 1980). These basins lie both on the Precambrian crystalline schists (Werenskiold and Brattegg), often with marble and calcite inserts (Fugleberget), and in the area of Old Paleozoic limestones and dolomites (Nordfall). In the basins mentioned above investigations were performed in the polar summer (July—September) and in the basins of the Werenskiold Glacier and Fugleberget over the whole year, also including the polar night in 1979 and 1980.

This paper contains preliminary results of the investigations performed in the Fugleberget basin in 1979 and 1980, under the framework of expeditions organized by the Institute of Geophysics of the Polish Academy of Sciences. Laboratory work, including the determination of the chemical composition of water and cryochemical experiments, was carried out in the hydrochemical laboratory of the Silesian University set in the main building of the Polish expedition, in the vicinity of the Fugleberget basin under study.

2. Geomorphological and geological characteristics

Within the limits of the topographic divide the Fugleberget basin has an area of 1.28 km^2, including the 0.22 km^2 lower, flat part within the marine terraces. The real area of the basin, in view of the large inclination of the slopes, is greater than the topographic one, being 1.36 km^2. The lowest point of the basin is the crossing of the Fuglebekken by the storm bank, at about 15 m a.s.l. The lower part of the basin lies at 15 to 50 m above sea level. (Fig. 12). The highest point of the basin is the peak of the Fugleberget (569 m a.s.l.).

More than 80 per cent of the Fugleberget basin is taken up by the slopes of the mountains Fugleberget and Ariekammen, lying at about 50 m a.s.l. to more than 500 m a.s.l. (Fig. 11). The slopes are covered with washed rubble sediments. There are large number of solifluction tongues and block streams (Martini 1975). In the upper part of the slope, between the peaks of the Fugleberget and the Ariekammen, there is a nival pothole drained by a steep chute which is closed at the foot by a classical alluvial cone. The peak of the Fugleberget is cut by several gullies, also closed by alluvial cones. Solid rock uncovered with loose sediments covers greater area on the steep slopes of the Fugleberget than on the gentler slopes of the Ariekammen. Flattenings of the slopes are covered with tundra vegetation, mostly mosses. The slopes of the Ariekammen and part of those of the Fugleberget are the nesting grounds of the little auk (Plautus alle); there are many thousands of these birds here.

The lower, flat part of the Fugleberget basin, covering about 20 per cent of the whole area, lies at 15 to 50 m a.s.l. It is situated within the raised marine terraces lying at 17, 25, 32, 45, 52 and 61 m a.s.l. (Jahn 1965). These terraces have preserved storm banks and are framed with rocks—the previous skerries and cliffs. The terraces are covered with sea gravel,

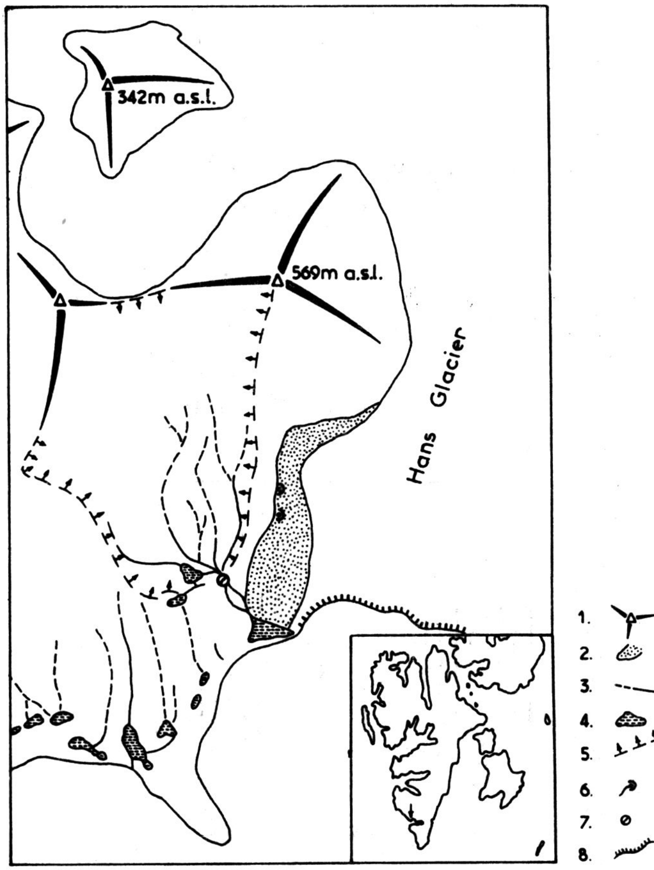

Fig. 1. A draft of the Fugleberget basin on the northern shore of the Hornsund Fiord. 1—mountain ridges, 2—lateral moraine of the Hans Glacier, 3—streams, 4—water reservoirs, 5—boundary of the basin of the Fugle stream, 6—springs, 7—hydrometric profile with liminigraph, 8—front of the Hans Glacier

sediments from the process of erosion of small rocks and cliffs and snad silt sediments in the weakly drained areas of the basin. In the lower part of the basin there is a small water reservoir which does not dry in summer and which has arisen on the storm bank of the 17 m terrace. Despite the slight inclination of the surface of this part of the basin, some surface solifluction movment can be observed. It is particularly distinct around the degraded rocks and cliffs and in the wide beds of the water streams

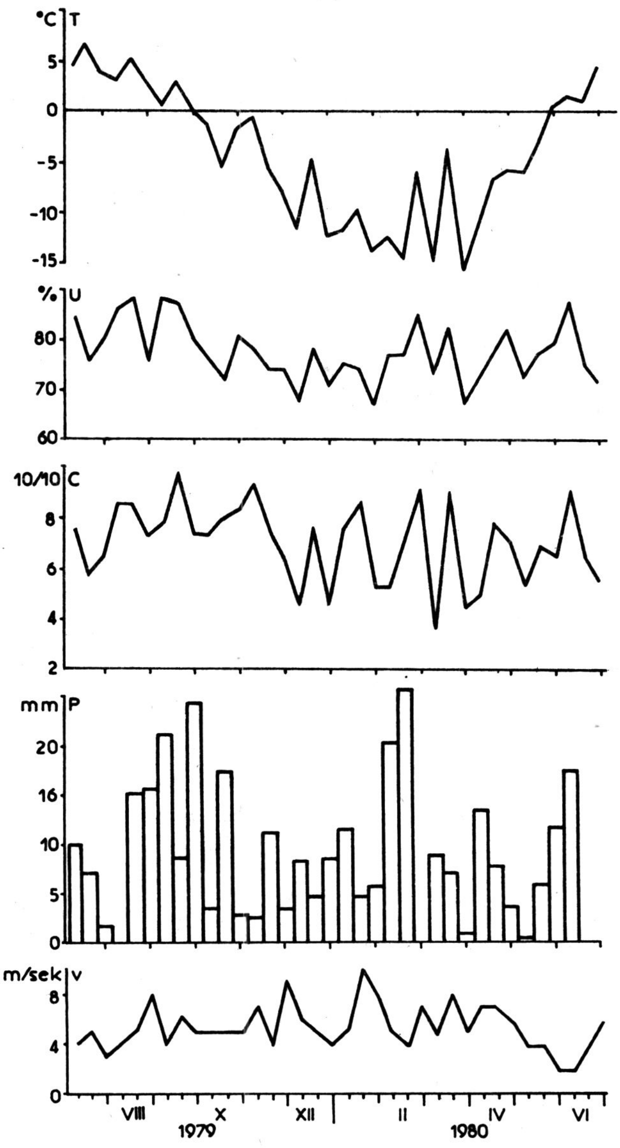

Fig. 2. Yearly variation in air temperature (T), relative air humidity (U), cloudiness (C), prepitation (P), wind speed (V) according to the decade means of the period 1979/1980 at Hornsund

flowing at the foot of the slope. Forms of frost segregation, e.g. patterned grounds are common here. The part of the basin described here is covered with tundra vegetation, in which mosses and saxifrages prevail. There is a great deal of lichens on rock blocks and outcrops of solid rock. Geese (Branta leucopsis) and skuas (Stercorarius parasiticus) nest here and there are many holes of the polar fox (Alopex lagopus).

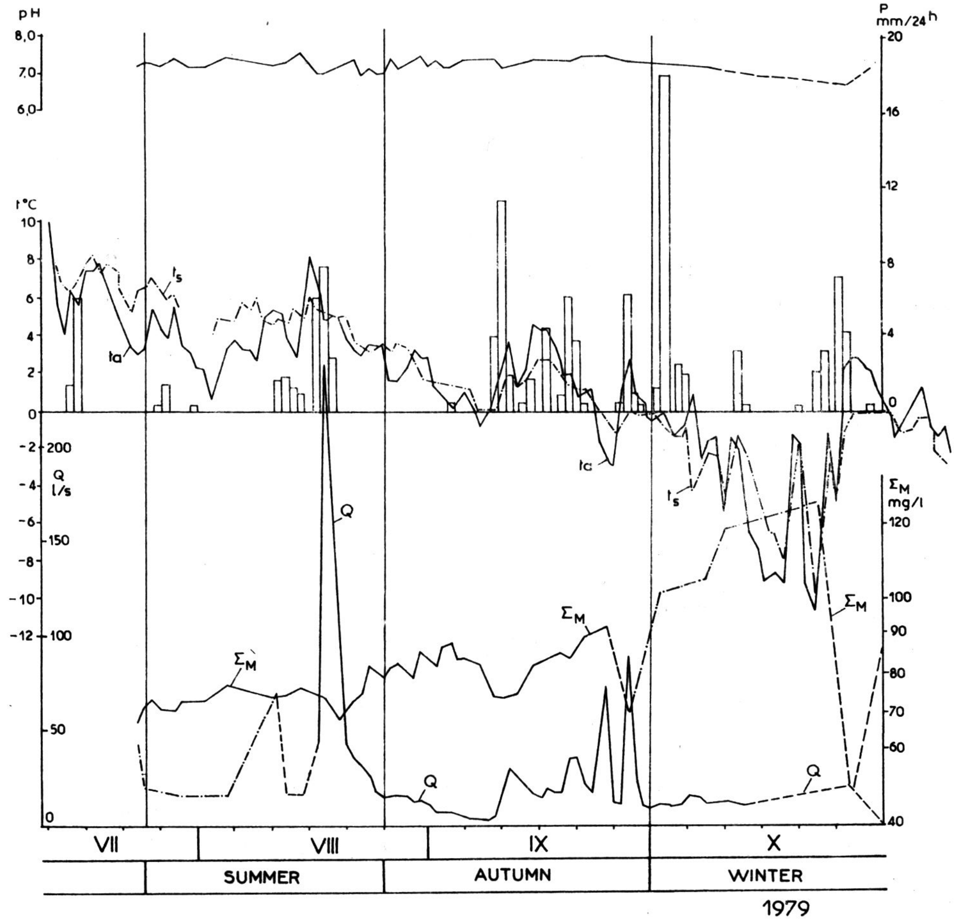

Fig. 3. Curves for hydrological, hydrochemical and neteorological elements for the Fugleberget basin in 1979. Q—flow, mean 24-hour values, Σ_M—total mineralization, pH—reaction, t_a—mean 24-hour ground temperatures at depth of 5 cm, P—24-hour precipitation total

The Fugleberget basin lies beyond the direct range of the final glaciation phase. The maximum range of the lateral moraine of the Hans Glacier has not reached the eastern boundary of the basin. Therefore, the basin has been shaped by: 1. Litoral processes (well formed marine terraces), since the seashore has reached the foot of the mountain slope. 2. Slope processes, which are intensive on the mountain slopes. The effect of these processes are rock streams and solifluction tongues. Similar processes, but on a smaller scale, have affected rocks, the previous skerries and cliffs. 3. Fluvial processes which in the upper part of the basin caused a washing of the slope cover and sedimentation in the lower part, 4. Processes occurring in the active layer of permafrost (solifluction, frost segregation). 5. Intensive processes of chemical denudation, particularly in rocks containing carbonates.

The basin is formed of metamorphic rocks of the Isbjornhamna formation belonging to Precambrian Hecla Hoek formations (Birkenmajer, Narębski 1960). There are mica schists and paragneisses with numerous intecalations of grey and yellow marbles and mica schists with calcite (Smulikowski 1965). The presence of marbles was found on the southestern slopes of the Fugleberget and the underslope surfaces in the eastern part of the basin. Mica schists with calcite occur primarily on the southern slopes of the Ariekammen and in the belt of rocks closing the basin in the west and east. The latter rocks are easily distinguishable because of their characteristic, eroded surface with perfectly visible structure (Fig. 13).

3. Meteorological conditions

Meteorological investigations carried out by all Polish expeditions at Hornsund and data given in papers about other areas of Spitsbergen (Baranowski 1968, 1977; Hisdal 1976, Markin 1975, Pereyma 1981) permit a general characterization of the climate conditions in the basin of the Fugleberget covered by field investigations.

Table I gives the basic metereological elements in the form of monthly values, while their yearly behaviour is characterized in Fig. 2. The meteorological data from the station at Hornsund agree well with the flat part of the hydrological basin under study, in view of the direct vicinity and the similar character of the bedrock. A considerable change in metereological conditions should be expected for the mountain part of the basin. In the light of the investigations at Hornsund, air temperature drops can be assumed with an average gradient of 0.6°C/100 m, and an almost double increase in precipitation (Pereyma 1981).

A dominating influence on the weather conditions at Hornsund is exerted by circulation. In summer the influence of the Iceland-Kara depression row in South Spitsbergen gives weather conditions with moderate air temperature at 24-hour means from 2 to 4°C. The damp masses of sea air cause considerable cloudiness which stabilizes over the mountain and glacial coast of Spitsbergen. As a result, this imposes a large restriction on the access of solar radiation to the surface of the tundra. Precipitation in summer is rain or drizzle at not-too-large intensity. It was found in 1979 and 1980 that large variations in terms of total precipitation can occur between particular summers. The period of summer metereological conditions lasts on average from the last decade of June to the end of August. Autumn, which lasts until the beginning of the polar night, is a period of increased cyclonic circulation and, therefore, of greater precipitation totals, variation in the atmospheric pressure and faster winds. When the sun is low over the

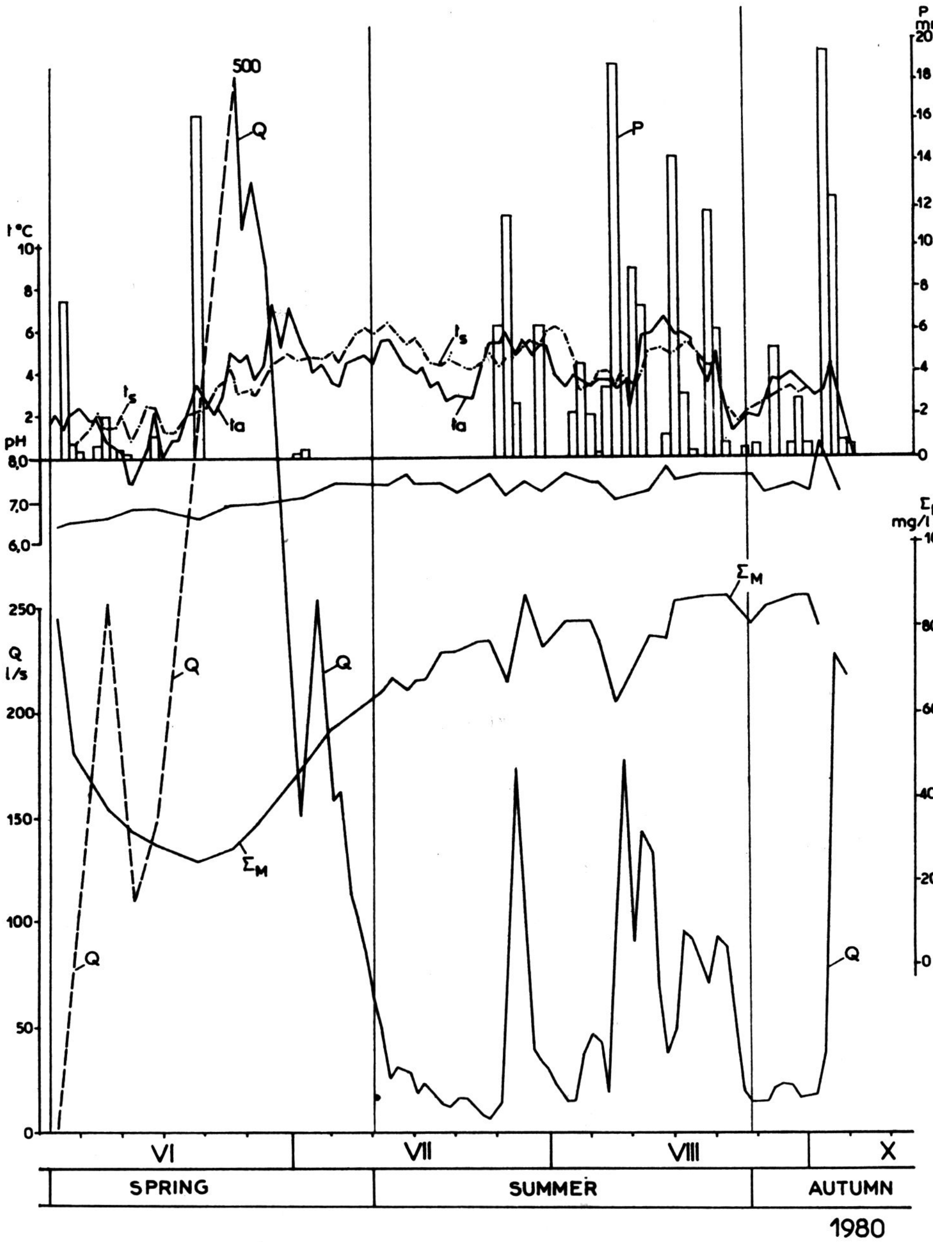

Fig. 4. Curves for hydrological, hydrochemical and meteorological elements for the Fugleberget basin in 1980. Q—flow, mean 24-hour values, Σ_M—total mineralization, pH—reaction, t_a—mean 24-hour air temperature at a height of 2 m, t_s—mean 24-hour ground temperatures at a depth of 5 cm, P—24 hour precipitation total

horizon and it is very cloudy, little solar energy comes through. The mean 24-hour air temperatures at Hornsund at that time of the year 1979 varied

Table I.

Atmospheric pressure (p, hPa) air temperature (T, °C), relative air humidity (U, %), wind speed (V, m/s), cloudiness degree (C, 10/10) according to monthly means and the monthly totals of precipitation (P, mm) at Hornsund in the period 1979/1980 Lubomirski and Swerpel 1980.

	VII	VIII	IX	X	XI	XII	I	II	III	IV	V	VI
p	1014.9	1013.8	1000.8	1013.5	1002.7	1001.2	1013.6	1005.5	1018.8	1011.9	1020.7	1013.7
T	4.9	3.7	1.2	−2.9	−4.9	−9.5	−11.9	−11.1	−11.6	−8.1	−3.0	2.4
U	80	83	85	76	75	72	72	79	74	77	76	78
v	4.2	5.7	5.1	5.0	6.7	5.2	7.8	5.3	6.0	6.9	3.3	4.0
C	5.6	7.7	7.9	8.3	8.1	6.6	7.2	7.1	5.7	6.6	6.3	7.0
P	18.5	21.8	44.6	16.2	17.4	23.9	51.8	11.5	11.5	21.5	19.4	28.8

from 3 to—10°C and impermanent snow cover began to form. The first days of the polar night were the last longer period of positive temperatures and liquid precipitations. Under the night temperature drops they did not make it possible for surface waters to flow to the fiord.

Winter, which lasts longest in Spitsbergen, i.e. from November to May, was characterized by greater weather dynamics in the early season of 1979/1980, which coincided with the polar night. Large air temperature drops, below—30°C, alternated with thaw periods when temperature rose above 0°C. The second part of the winter, from the end of February was characterized by more stable frost weather. Under these conditions the snow cover was finally formed in the area of Hornsund, reaching its maximum thickness at the beginning of May 1980. The height of the snow cover in the flat of the Fugleberget basin was at that time 0,7 m on average and 1,5 m in the slope part. The snow in the winter 1979/1980 at Hornsund was characterized by high density (over 0,5 g/cm^3) and a high water equivalent, which was estimated as about 600 mm on average for the Fugleberget basin (Pereyma 1981 a).

The spring of 1980 was characterized by an increase in air temperature to about 0°C and small precipitations. Under these conditions the snow cover in the Fugleberget basin disappeared rather slowly and the patches of snow feeding the streams did not thaw until the beginning of July. The summer of 1980 was characterized by much more precipitation that the previous summer season. This is illustrated by precipitation totals determined for particular hydrological seasons in the basin under study (Table II).

4. Hydrological characteristic

In the basin water levels were registered in two hydrometric profiles. Profile 1 was set in the Fugle stream which takes water from the whole basin (Fig. 1). profile 3 in the undrying water reservoir (Fig. 12.) Complementary systematic measurements were taken in the profile 2 (the stream flowing from under the cliff rocks in the eastern part of the basin) and 4 (the stream flowing to the reservoir from under a gully on the slope of the Ariekammen). In addition several measurement series were taken in a dozen or so streams.

In 1979 the active hydrological period in the Fugleberget basin lasted for more than 4 months. It began in the middle of June and ended on the last day of October. In 1980 the outflow from the basin began two weaks earlier, at the beginning of June and ended probably in the middle of October. There was an attempt to divide this "polar hydrological year" of more than four months into four hydrological seasons. At beginning

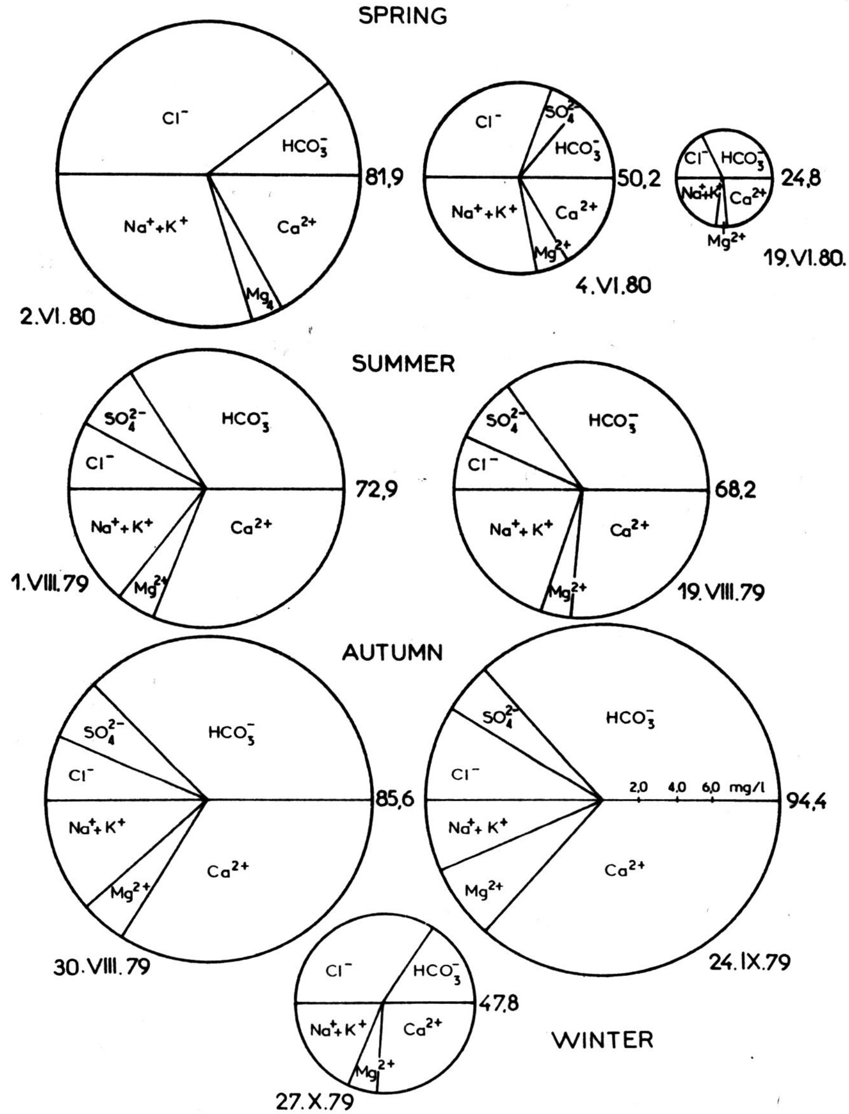

Fig. 5. Circular diagrams for the ionic composition of selected water from Fugle stream in the hydrological seasons in 1979 and 1980

of the climatological winter of 1979 outflow from the basin was found, providing the reason for distinguishing the winter hydrological season. The season were distinguished on the basis of hydrological and climatological criteria. The basis of the hydrological criterion was an analysis of the curve for water levels and its variation, mainly over 24-hour periods, and a differentiation of water types flowing from the basin. In turn the climatological criterion was based on the mean 24-hour value of air temperature at a height of 2 m over the ground and the variation of the ground temperature at depth of 5 cm. Greatest differences in the leght of hydrological seasons with respect to thermal ones occurred at the transitions spring-summer and summer-autumn (Table II, Figs. 3, 4).

The spring season (2 June — 10 July, 1980) was characterized by highest water levels (with maximum outflow — 500 l/s, mean outflow — 229.3 l/s. The curve of the spring flows progresses into one great culmination with a maximum in the second half of the season. The water dropped very rapidly, more rapidly than the previous increase in flow. The intensive spring rainfalls effected the beginning of water flow precipitation on 2/3 June, of 7.4 mm) while the greatest precipitation in this season (16.1 mm on 19 June) caused largest flow on 23 June. The spring season mainly involves the outflow of the water from thawed winter snow. The water reserve in snow, as determined in the Fugleberget basin at the end of winter, was 636 mm. The contribution of the precipitation water which fell in spring (29.3 mm) was therefore realtively small, but it affected the rapid thawing of the snow cover. 594,3 mm water flowed from the basin in the spring season, i.e. about 90 per cent of the water in this area in spring (the water reserve in snov and spring precipitation). In the end of the spring season the rapid flow of thaw water disappeared, to be followed by the outflow of water from defreezing permafrost and precipitations.

The summer season (11 July—24 August, 1980) was characterized by high variation in water levels, with large precipitation of 109.8 mm (maximum flows exceeded 170 l/s, minimum ones were below 10 l/s, mean 53 l/s, (Fig. 4). The flow curve shows three distinct culminations lasting several days and divided by periods of very low outflow also several days long. Summer began with a 15-day period of very low discharge. High levels occurred in the period of very strong precipitation, thawing permafrost and of the remaining snow cover in the higher parts of the mountains. Ariekammen and Fugleberget. 158.8 mm water flowed out in the season.

Compared to the summer of 1980 the summer of 1979 (25 July—25 August was characterized by similar variation in discharge with three distinct culminations. There were, however, essential differences, namely in the amount of precipitation water, only 23.5 mm in the summer of 1979 (1/5 of the summer of 1980) and in differentiated flow culminations. The first two discharge culminations reached only a value of 70 l/s whereas the third, at the end of the season, exceeded 300 l/s. Minimum discharge fell below 20 l/s. The mean discharge was 51.7 l/s and was close to the summer discharge of 1980. Throughout the summer of 1979 109.9 mm flowed from the basin.

The autumn season (26 August—30 September, 1979) was characterized by variable water levels. The maximum discharge which came at the end of the season, reached 80 l/s, with a mean seasonal outflow of 18.9 l/s.

Three periods can be distinguished on the discharge curve. The first period lasted until 9 September and involved minimum discharge below 10 l/s. The second ended on 22 September, with discharge varying between 15—35 l/s. The third, until 30 September, involved a rapid increase in discharge which, through two short culminations, reached 90 l/s. The end of this period showed

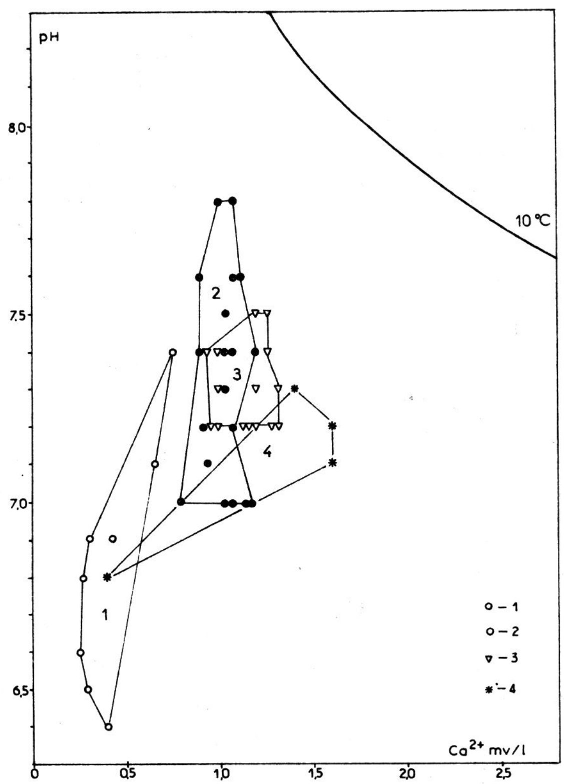

Fig. 6. Carbonate corrosive power of the water from the Fugle stream in 1979 and 1980 on a Tillmans-Trombe-Muxart diagram. 1—spring, 2—summer, 3—autumn, 4—winter

a rapid decrease in flow down to about 10 l/s. The last two periods were caused by intensive rainfalls, with a total of 44.8 mm. This precipitation was instantaneously drained from the basin and was equivalent to the outflow, the latter being, when recalculated in mm, 45.2 (Table II). At the end of this season the air temperature decreased greatly, the ground temperature at a depth of 5 cm fell below 0°C and water began to cumulate in the active zone of permafrost.

The winter season (1 October—31 October, 1979). which began when the ground temperature fell below 0 °C and ended when the outflow totally disappeared, was characterized by low and very low discharge (the mean outflow being 11.6 l/s). As a result of intensive rainfalls and a raise in air temperature above 0 °C, the outflow began anew, to exceed 20 l/s in culmination. Finally, all outflow stopped at the end of October. At the beginning of the polar night in October, there was an outflow from the Fugleberget

Table II.

Comparison of outflow and precipitation in Fugleberget Basin, hydrological seasons 1979 and 1980

Hydrological season	Duration (days)	Outflow Q m^3/s	thou. m^3/season	mm	Prec. P mm	Q—P mm
summer 79	32	0.0517	142.9	109.9	44.6	86.4
autumn 79	36	0.0189	58.8	45.2	44.6	0.4
winter 79	31	0.0116	31.1	23.9	44.6	−20.7
water reserve in snow						
					(665.3)[1]	(−71.0)
spring 80	39	0.2293	772.6	594.3	29.3	565.0
summer 80	45	0.0531	206.5	158.8	109.8	49.0
hydrological year 1979/1980 26.08.79—24.08.80						
	151	0.082	1069.0		(864.5)	(−42.3)
				822.2	228.5	593.7

[1] The values in the brackets take into account snow water from the winter season, which outflows in the spring season

basin, draining almost half the precipitation of that month. The other water (20.7 mm) remained in the basin. It filled the empty space in the active zone of the ground and solidified until spring as naled ice.

5. Physico-chemical properties of water

The chemical composition of the surface water in the Fugleberget basin was determined at a field laboratory (Markowicz, Pulina 1979). Water samples for this purpose were taken in the hydrometric profile of the Fugle stream from 23 July, 1979 on, every day or every two days, at about 20 hours GMT. When the samples were taken, the temperature of the water was also measured. Samples were put into 0,5 l polyethylene bottles. The value of pH was determined colorimetrically, with an accuracy of 0.1 pH unit, most frequently in field and at times in the laboratory, not longer than on one hour after the samples had been taken. Simultaneously, the content of free carbon dioxide was determined colorimetrically, with an accuracy of 0.1 pH unit, most frequently in field and at times in the laboratory,

Table III.

Chemical denudation in Fugleberget Basin 1979 — 1980.

Hydrological Season	Duration (days)	Q_{av} m^3/s	q_{av} L/skm^2	T mg/l	T mg/l	Chemical denudation m^3	Chemical denudation t	Chemical denudation m^3/km^2	Ionic flow m^3	Ionic flow t
Polar hydrological year 1979										
spring 25.06—24.07	30									
summer 25.07—25.08	32	0.0517	39.8	74.6	57.1	3.3	8.2	2.5	4.3	10.7
autumn 26.08—30.09	36	0.0189	14.5	82.3	64.8	1.5	3.8	1.2	1.9	4.8
winter 1.10—31.10	31	0.0116	8.9	96.3	78.8	1.0	2.4	0.8	1.2	3.0
Polar hydrological year 1980										
spring 2.06—10.07	39	0.2293	176.4	40.8	23.3	7.2	18.0	5.5	12.6	31.5
summer 11.07—24.08	45	0.0531	40.8	75.3	57.8	4.8	11.9	3.7	6.2	15.5
Polar hydrological year 1979/80										
25.07.79—10.07.80 (1)	138	0.0810	62.3	—	—	13.0	32.4	10.0	20.0	50.0
26.08.79—24.08.80 (2)	151	0.0819	63.0	—	—	14.5	36.1	11.2	22.0	54.8
Precipitation (1)		—	—	17.5	—	7.0	17.6	5.5	—	—
Precipitation (2)		—	—	17.5	—	7.5	18.7	5.8	—	—

not longer than one hour after the samples had been taken, by the method of titrating the sample with a Na_2CO_3 solution in the presence of phenolpthalein (with an accuracy of 1 mg). The remaining analyses were mostly carried out within 12 hours after the smaples had been taken. The total

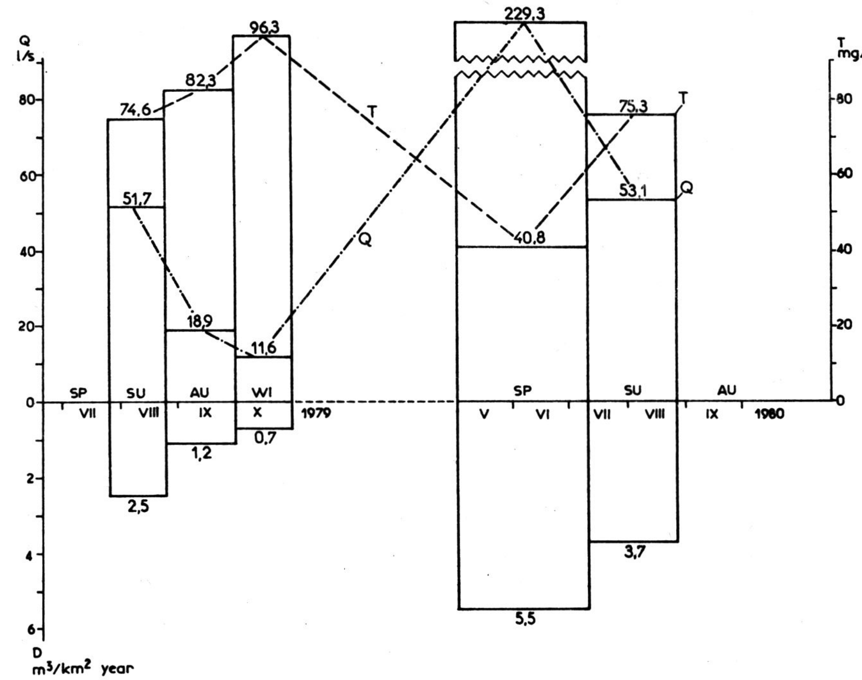

Fig. 7. The relation of water mineralization (Σ_M) and outflow (Q) to the magnitude of chemical denudation (D) in the Fugleberget basin in the hydrological seasons in 1979 and 1980.

hardness was determined by the versenate method, in the presence of eriochrome black as the indicator; calcium was also determined by this method, in the presence of murexide. The magnesium content was calculated from the difference between total hardness and calcium content. The bicarbonate alkalinity was determined by titrating the sample with a hydrochloric acid solution in the presence of methyl orange. Chlorides were determined argentometrically, whereas the sulphate content was defined using an indirect versenate method. In addition the content of silica ionized by the method of reduction to silico-molybdic blue was determined spectrophotometrically in the water samples. The electrical conductivity of the water from which total mineralization would be calculated later, was also determined.

Figs. 3 and 4 show curves for total mineralization (Σ_M) and the concentration of hydrogen ions (pH) and also the water temperature, whereas Fig. 5 gives circular diagrams illustrating the ionic composition of selected water samples, typical of each of the hydrological seasons. The aggressiveness of the water was analyzed on the Tillmans-Trombe-Muxart diagram (Fig. 6), while the mean seasonal values of total mineralization are shown in Table III.

In the spring season the total mineralization was high (81.9 mg mg/l) when the hydrological period began, and subsequently its gradual decrease to a minimum value (24.8 mg/l) and again its increase could be observed. The spring season water was characterized by low values of pH, from 6.4 to 7.4 with a tendency to rise gradually. On the basis of the curves of Σ_M, pH and water temperature and the diagrams of the ionic composition of water, two spring water types can be distinguished: snow water with an unchanged ionic composition close to precipitation water, i.e. water of the type Cl^- — $(Na^+ + K^+)$ — Ca^{2+} and water transformed as a result of a dissolution of carbonate rocks, of the type HCO_3^- — Ca^{2+} — $(Na^+ + K^+)$. In the first dozen or so days the total mineralization of the water of the spring season in 1980 reached relatively high values (about 80 mg/l). This period was followed by further intensive dissolution of carbonate rocks. The remaining part of the summer was different from the previous period in the stabilized mineralization level of above 80 mg/l, broken several times by mineralization decreases caused by intensive rainfalls. In the first, rainless period of the summer season the values of pH were stable, i.e. 7.4; on the other days a distinct dependance on precipitation could be seen. The rainfalls were accompanied by a decrease of about 0.5 unit in pH. In the summer period the water of the type HCO_3^- — Ca^{2+} — $(Na^+ + K^+)$ flowed from the basin despite there being two genetic water types. At the beginning of the summer there was aggressive snow water and precipitation water in other part of the season. The summer of 1979 had a curve of mineralization and pH similar to that of the summer of 1980.

In the autumn season of 1979 the total mineralization increased, reaching its maximum at the end of the season (above 100 mg/l). At that time it was possible to observe slight variations in mineralization caused by precipitations. The pH curve had behaviour close to that of the summer period. In the autumn season one water type dominated, namely water of the type Ca^{2+} — HCO_3^- — Cl — (Fig. 5). This was precipitation water. At the end of the autumn season high values of mineralization could be observed even at relatively large flows. This phenomenon can be explained by the cryochemical effect (Pulina 1985) caused by the retention capacity of the active layer.

In the winter season of 1979 two parts can be distinguished in the curve for mineralization variation. The first covers the larger part of the season where an increase in mineralization up to about 120 mg/l could be observed. This was a continuation of the tendency which occurred at the end of the autumn season. This processes may probably have been caused by a cryochemical effect. Water of the type HCO_3^- — Ca^{2+} — $(Na^+ + K^+)$ occurred here. The other part of the curve, covering the other days of the winter season, was characterized by relatively low mineralization, lowering to 50 mg/l, and the presence of a different water type, $Cl^{-} - Ca^{2+} - (Na^{+} + K^{+})$, mostly from precipitation. Also here the two water types mentioned above can be distinguished in the behaviour of the pH curve; the first with pH values over the range 7.1—7.4 the other, belov 7.0. It was characteristic of the end of the winter season that these two water types mixed.

6. Chemical denudation

The measure of the magnitude of chemical denudation is the thickness of the removed surface of the degraded rocks, most often expressed in mm/thousand years, or the thickness of the removed rock mass in m^3/km^2

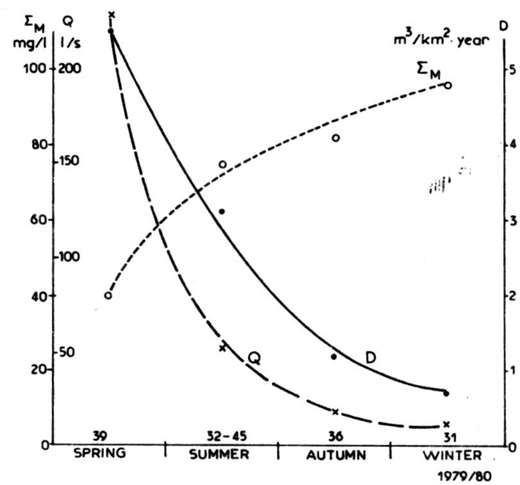

Fig. 8. Total mineralization (Σ_M), outflow (Q) and chemical denudation (D) in the four seasons in the polar hydrological year 1979/1980 in the Fugleberget basin.

year. Chemical denudation in Spitsbergen, mainly in carbonate rocks, was investigated by Corbel (1959), Hellden (1973) and one of the authors of the present paper (Pulina 1974, 1977).

The magnitude of chemical denudation in the Fugleberget basin was calculated from the following formulae (Pulina 1974a):

$$A_m = 0.03456 \cdot T \cdot Q \cdot t, \quad (1)$$

$$A_t = 0.0864 \cdot T \cdot Q \cdot t. \quad (2)$$

These formulae result from the basic relation

$$D_m = 12.6 \frac{T \cdot Q}{P}, \tag{3}$$

where D_m is chemical denudation, expressed in m^3/km^2 year or mm/1000 years; A_m and A_t is the volume of denuded rocks in m^3 (A_m) and in tons (A_t) for a given period t, in expressed in 24-hour intervals; ΔT is the content (in mg/l) of salts dissolved in the water leaving the basin and coming from the natural process of rock dissolution; it is defined by the formula $\Delta T = T - T_a$, where T is the real water mineralization in mg/l and T_a is the content of salts from outside of the area under study (allochthonic water) — in the Fugleberget basin this is precipitation water; Q is the outflow from the basin under investigation, mean for a given period and expressed in m^3/s; and P is the area of the basin in km^2. Table III shows the results of calculations of chemical denudation for the particular hydrological

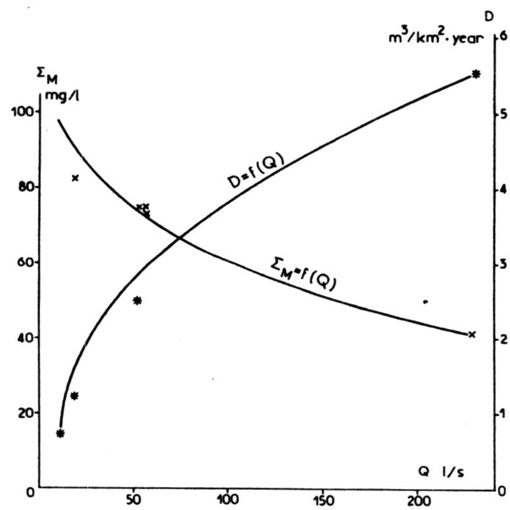

Fig. 9. The dependence of water mineralization on outflow ($\Sigma_M = f(Q)$ and of chemical denudation on outflow ($D = f(Q)$ in the Fugleberget basin in the polar hydrological year in 1979 and 1980

seasons and for polar hydrological year 1979/1980. This table also shows the magnitude of salts from precipitation. Chemical denudation was calculated with respect to total mineralization.

Over the 4.5—5 months of the polar hydrological year the denuded rock volume is 10.0—11.2 m^3/km^2 year. In the particular hydrological seasons it varies from 0.8 m^3/km^2 in winter to 5.5 m^3/km^2 in spring. The rock volume removed from the whole surface of the basin, more than 1.3 km^2, is from 13.0 to 14.5 m^3/year. The real volume of salts drained from the Fugleberget basin, i.e. the so-called ionic run-off is from 20.0 to 22.3 m^3/year, but this volume also includes precipitation salts (7.0—7.5 m^3/year), which are not the effect of rock dissolution in the Fugleberget basin. These are nearly 30 per cent of transported salts and must be taken into account, particularly in the polar areas with their circulation of relatively law mineralized water. The magnitude of chemical denudation is in direct proportion to the discharge while mineralization is in inverse proportion to the later (Fig. 7, 8 and 9).

In view of the fact that the surface of the carbonate rocks (marbles and calcite) takes an estimated 1/5 of the whole area of the Fugleberget basin, the real magnitude of chemical denudation of these rocks is five times as much and can even exceed 50 m^3/km^2 year. This large value of chemical denudation found in the Fugleberget basin results from the specific geological structure. The presence of marble inserts and calcite veins in the hardly dissoluble mass of acid rocks facilitates the corrosion of carbonate rocks (Fig. 13). The saturation of the strongly aggressive water occurs at the expense of carbonate rocks which take only a relatively small area among the non-karstic rocks. The small carbonate capacity of this water can thus be used only for dissolution of carbonate inserts. If the whole basin were built of carbonates, the effect of chemical denudation would be several times as small i.e. the magnitude of the rock mass removed chemically could be the same in both casses but its distribution within the basin would differ, depending on the percentage area covered by soluble rocks.

Chemical denudation of weakly soluble rocks, including silicate rocks, was also found in the Fugleberget basin. Some part of the mass of these rocks is ionized silica which is also drained from the basin. The establishment of this fact is of large significance for the explanation of the mechanical disintegration of rocks under the conditions or the polar climate.

7. Conclusion

The most important result of the present paper is an attempt to determine the water balance and the chemical denudation balance in the Fugleberget basin. Here are some remarks on the calculated elements making up this balance (Fig. 10).

7.1. Despite the short hydrological year, in the basin there was a considerable amount of water, determined as above 800 mm. This value is close to the quantities occurring in the lowlands and highlands of Central Europe. This fact is the best evidence of the dynamic hydrological processes in the polar basin. The basin water supply comes mostly from winter retention reserves in snow and ice (above 600 mm). The other water circulating in the basin comes from precipitations which affect the outflow from the basin in the autumn and winter seasons.

7.2. The Fugleberget basin is supplied only by precipitations. The amount of this precipitation water exceeds the outflow from the basin. This difference is small, i.e. more than 40 mm. Thus the basin has a small positive balance.

7.3. The basin is active for barely 4 to 5 months a year. Despite this short duration all typical phenomena occur in the four short hydrological

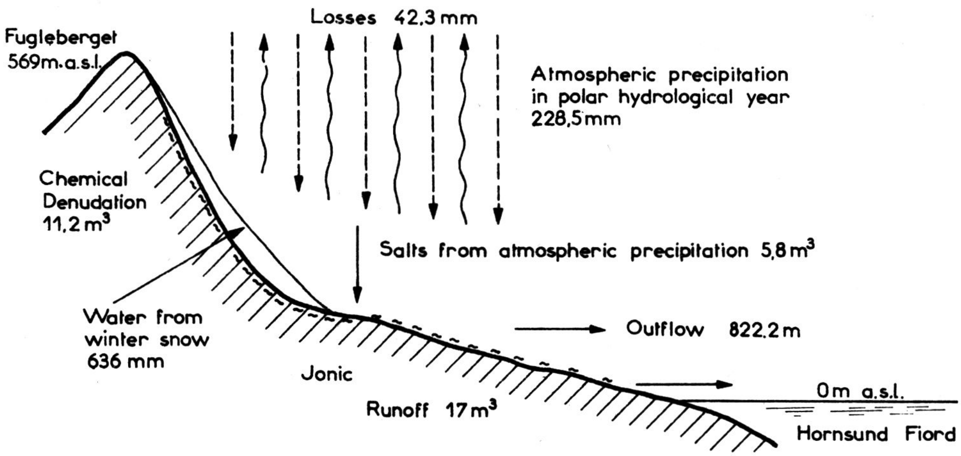

Fig. 10. Schematic water balance and chemical denudation in the Fugleberget basin. The polar hydrological year 1979/1980

seasons. What is striking here is the greatly dynamism of hydrological processes: the intensive spring outflow and the high flood level in summer or autumn. These alternate with short depression periods, some with such low states that most surface water disappears.

7.4. In the course of the short polar hydrological year about 17 m^3 of dissolved salts per each km^2 of the basin flows to the sea; of this 11.2 m^3 comes from the real rock dissolution. The other 5.8 m^3 is made up of precipitation salts which are allochthonic in the basin. This indicates that only 1/3 of the salts drained to the sea returns in the year cycle, while the remaining 2/3 the real denudation effect.

7.5. The schematic water and denudation balance (Fig. 10) does not take into account the effects of chemical denudation in the water and solian environment. The dissolution of silicate rocks and the drainage to the sea of silica in ionized form, which were found in the course of the investigations in the basin, indicate that even crystalline rocks erode chemically in the polar climate. A separate problem is that of the local transport of mineral particles within the basin. There is a large amount of them and, as Jahn (1961) claims on the basis of investigations performed here in 1957–59, mechanical transport caused by washing out can reach

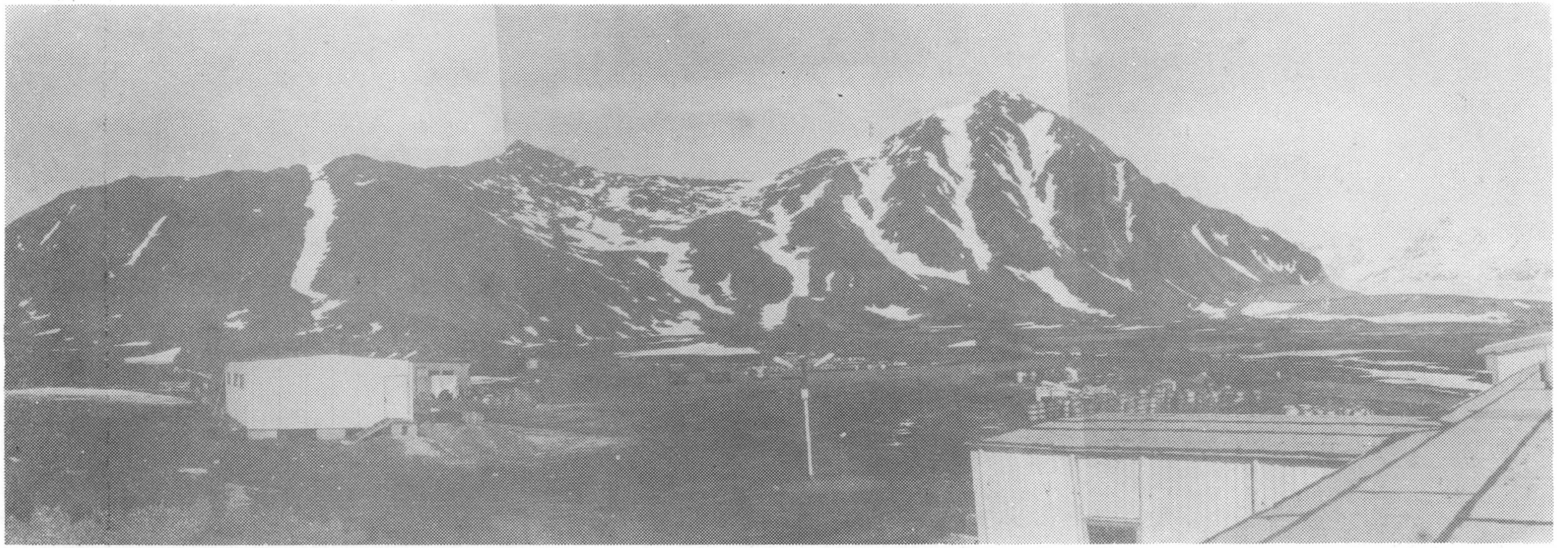

Fig. 11. The Fugleberget basin seen from the roof of the Polish Polar Station at Hornsund. Spring 1980. Taken by M. Pulina

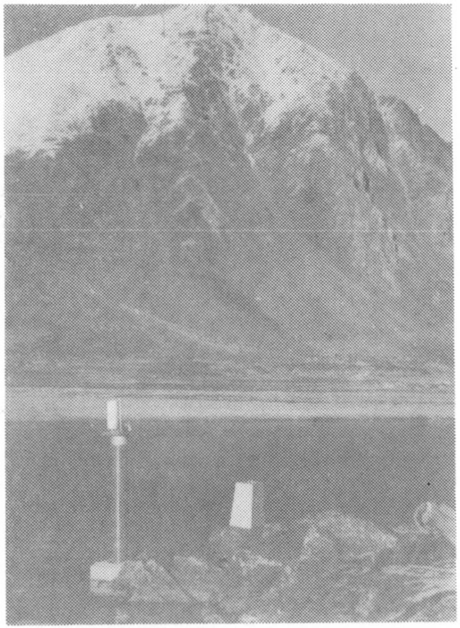

Fig. 12. The Fugleberget basin. A limnigraph on the lake (hydrometric profile no. 3). The basin covers the slopes of the Fugleberget (569 m over the sea level) and raised sea terraces at the foot of the the slopes. September 1979. Taken by M. Pulina

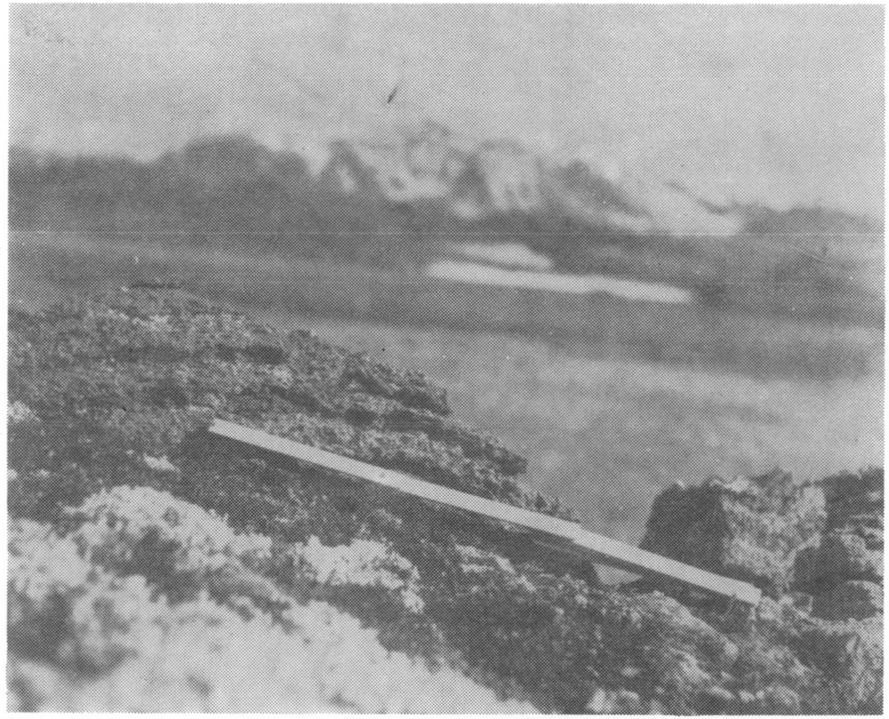

Fig. 13. Corroded micaceous slates with clacite inserts in the Fugleberget basin (rule lenght of 50 cm). Zaken by M. Pulina

1–16 t/km^2 year. Certainly part of this mass fills local hollows; a considerable par of it, however, leaves the basin and should therefore be considered in the denudation balance. Of importance is also the denudation affect caused by strong winds which blow here with great intensity, particularly at the end of autumn and in the first winter months. This process is strengthened by the lack of compact snow cover in that period. Therefore, taking into account the effects of fluvial and eolian transport, the total (chemical and mechanical) denudation in the basin is least a dozen or so m^3/km^2 year.

8. Резюме

Даны результаты исследований, проведенных в бассейне Фулгебергет, расположенном на северном побережье фиорда Горнзунд, на непокрытой льдом территории высоких морских террас и на склонах гор Фуглебергет (569 м н.у.м.) и Ариекаммен (511 м н.у.м.). Исследования проведены в период от 23 июля 1979 г до 4 сентября 1980 г включая время полярной зимы. Бассейн Фуглебергет характерен для непокрытих ледниками морских террас и гор, лежащих у моря. Они занимают в западном Шпицбергене большие пространства, где распространена многолетняя мерзлота.

Целью исследований было изучение флювиальных явлений таких как: продолжительность гидрологического периода, способ снабжения бассейна водой и опыт определения элементов водного баланса. Кроме того изучались гидрохимические процессы, главным образом изменение химического состава воды и размеры химической денудации.

9. Streszczenie

Artykuł zawiera wyniki badań przeprowadzonych w zlewni Fugleberget położonej na północnym wybrzeżu fiordu Hornsund, na niezlodowaconym obszarze podniesionych teras morskich oraz na stokach gór Fugleberget (569 m npm) i Ariekammen (511 m npm). Badanie prowadzono w okresie od 23 lipca 1979 r do 4 września 1980 r, w tym również w czasie zimy polarnej. Zlewnia Fugleberget dobrze reprezentuje obszary teras morskich i gór nadmorskich, nie pokryte lodowcami a zajmujące duże powierzchnie na zachodnim Spitsbergenie. Obszary te charakteryzują się występowaniem zmarzliny.

Celem badań było rozpoznanie zjawisk fluwialnych takich jak: długość trwania okresu hydrologicznego, sposób zasilania zlewni w wodę oraz próba określenia elementów bilansu wodnego. Ponadto przeprowadzono studia na temat procesów hydrochemicznych, a głównie zmian składu chemicznego wód oraz określono wielkość denudacji chemicznej.

10. References

1. Baranowski S., 1968 — Termika tundry peryglacjalnej (periglacial tundra), SW Spitsbergen. Acta Univ. Wratisl. No. 68, Wrocław.
2. Baranowski S., Głowicki B. 1975 — Meteorological and hydrological investigations in the Hornsund region made in 1970. Acta Univ. Wratisl. No 251, Wrocław.

3. Baranowski S. 1977 — Subpolar glaciers of Spitsbergen seen against the climate of this region. Acta Univ. Wratisl. No 410, Wrocław.
4. Birkenmajer K., Narębski W. 1960 — Precambrian amphibolite complex and granitization phenomena in Wedel-Jarlsberg Land, Vestspitsbergen. Studia Geol. Polon. IV, Warszawa.
5. Corbel J. 1959 — Erosion en terrain calcaire. Ann. Georg. 366, 68, Paris.
6. Głowacki B., Barański A. 1980 — Obserwacje meteorologiczne w Stacji PAN w Hornsundzie (Meteorological observations at the Station of the Polish Academy of Sciences at Hornsund) (unpublished).
7. Hellden U. 1973 — Some calculations of the denudation rate in a dolomitic limestone area at Isfjord-radio, West Spistbergen. Trans. Cave Research Group of Great Britain, 15, 2.
8. Hisdal V. 1976 — Geography of Svalbard. Norsk Polarinstitutt, Oslo.
9. Jahn A. 1961 — Quantitative analysis of some periglacial problems in Spitsbergen. Zeszyty Naukowe Uniw. Wrocł. B, 5, Wrocław.
10. Jahn A. 1968 — Raised shore lines and terraces at Hornsund, and postglacial vertical movements on Spitsbergen. (in:) Polish Spitsbergen Expeditions 1957–1960, Warszawa.
11. Krawczyk W., Pulina M. 1980 — Hydrochemical investigations carried out on the northern shore of Hornsund. (in:) Field investigations performed during the Spitsbergen expedition of the Silesian University in the summer of 1979. Katowice.
12. Leszkiewicz J. 1979 — Hydrochemical and hydrological investigations in Sorkappland. (in:) Field investigations performed during the Spitsbergen eypedition of the Silesian University in summer of 1978. Katowice.
13. Lubomirski K., Swerpel S. 1980 — Zestawienie danych meteorologicznych z Hornsundu 1979/1980. Wyprawa PAN na Spitsbergen (materiały). Meteorological data for Hornsund 1979/1980. Expedition of the Polish Academy of Sciences to Spisbergen).
14. Markin V. A. 1975 — Klimat oblasti sovremennogo oledenenia. Oledenienie Spitsbergena (Svalbarda). Nauka. Moskva.
15. Markowicz M., Pulina M. 1979 — Ilościowa półmikroanaliza chemiczna wód w obszarach krasu węglowego (Quantitative chemical semimicroanalysis of water in the carbonate karst areas). Silesian University, Katowice.
16. Martini A. 1975 — The weathering of beach pebbles in Hornsund. Acta Univ. Wratisl. No 251, Spitsbergen Expeditions I, Wrocław.
17. Pereyma J. 1983 — Climatological problems of the Horusund area, Spitsbergen. Acta Univ. Wratisl: No 714, Wrocław.
18. Pereyma J. 1981a — Pokrywa śnieżna w rejonie Fiordu Hornsund na Spitsbergenie (Sum. A snow cover in the region of Fiord Hornsund on Spitsbergen) VIII Sympozjum Polarne, Sosnowiec.
19. Pulina M. 1974 — Denudacja chemiczna na obszarach krasu węglanowego (Sum. Chemical denudation on the carbonate karst areas). Prace Geograficzne PAN, 105, Ossolineum, Wrocław.
20. Pulina M. 1974a — Preliminary studies on denudation in SW Spitsbergen. Bull. Acad. Polon. Sc., Ser. Sc. Terre, 22, 2, Warszawa.
21. Pulina M. 1977 — Uwagi o zjawiskach krasowych w południowej części Spitsbergenu (Res. Remarques sur les phenomenes karstiques dans le partie meridionale du Spitsberg). Kras i Speologia, 1(X), Katowice.
22. Pulina M. 1985 — Efekty procesów kriochemicznych w lodowcach i zmarzlinie na Spitsbergenie (The effects of cryochemical processes in the glaciers and permafrost in Spitsbergen), Polish Polar Research, Warszawa.

23. Smulikowski W. 1965 — Petrology and some structural data of lower metamorphic formations of the Hecla Hoek Succession in Hornsund, Vestspitsbergen. Studia Geol. Polon. XVIII, Warszawa.
24. Wach J. 1980 — Hydrological and hydrochemical investigations performed on the southern shore of Hornfund (in:) Field investigations performed during the Spitsbergen expedition of the Silesian University in the summer of 1979. Katowice.

Paper received in December 1981